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Abstract
Due to the increased bandwidth and decreased latency, Optical Network-on-Chip (ONoC) is a good solution for interconnect bottleneck in large-scale Multiprocessor System on Chip (MPSoC). It takes advantage of Wavelength Division Multiplexing (WDM) supporting multiple transactions at same time on different wavelengths. Hence, many senders and receivers can share the same waveguide to increase the total bandwidth utilization. However, multiple overlapped communications on different (close) wavelengths would inevitably introduce non-negligible crosstalk noise on optical signals in large-scale WDM 3D ONoC due to the low wavelength channel spacing and the large Full Width at Half Maximum (FWHM) of the resonance pic of the Microring Resonator (MR). This paper proposes a heuristic algorithm allowing to allocate wavelengths at design time in order to reduce the crosstalk noise. The simulation results show that the proposed heuristic algorithm achieves the same Wavelength Spacing Optimization (WSO) as that of Branch and Bound algorithm for MWD application, 43.75% reduction compared to naive method [10] .

Keywords: ONoC, Crosstalk Noise, Wavelength Allocation, Wavelength Spacing

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1. Introduction

Given the evolution of MPSoC, we currently focus on chips with hundreds of IP cores. To cope with huge communication requirement, Network-on-chip (NoC) design has been put forward to replace bus-based design. However, the limitation of electrical interconnects, such as capacitive and inductive coupling [7], interconnect noise and increased propagation delay of global interconnect, has severely hindered the further improvement of NoC. Thus a new on-chip interconnect technology that can overcome the problems of electrical interconnect is highly desirable. Progress in 3D integration technology and on chip optical device manufacturing allow to realize an ONoC. A 3D architecture based on an optical interconnection for an MPSoC is one of the key solutions to solve the questions above. It relies on optical waveguides carrying optical signals, so as to replace electrical interconnect and to provide low latency, high bandwidth properties and high noise immunity to the communication medium. The waveguide for payload transmission can be shared by multiple senders and receivers. Moreover, Wavelength Division Multiplexing (WDM) [5] is employed to support multiple transactions at same time. However, simultaneous transmissions, on closed adjacent wavelengths, may introduce crosstalk noise through different optical switching elements within the network which degrades system performance [4]. Thus we propose a heuristic algorithm to distribute wavelengths at design time

for purpose of reducing the crosstalk noise on optical signals. This is a generic algorithm which is compatible with other model of crosstalk [11] [3] [16] [2]. Our proposed heuristic method can reach an acceptable suboptimal solution compared to Branch and Bound algorithm according to the closed results obtained in both two methods, and a large reduction in WSO compared to naive method [10].
The rest of the paper is organized as follows. Section 2 presents overview of previous work. In section 3, we introduce the 3D optical many core architecture, detail the mathematical formalization of WSO and the proposed heuristic algorithm. Section 4 gives simulation results of WSO. Finally, section 5 concludes the paper and gives perspectives.

2. Related work

Optical signals of various wavelengths can interfere with each other through different optical switching elements within the network [11]. For closely-spaced wavelengths (Dense Wavelength Division Multiplexing channels), the inter-channel crosstalks vary in 23-30dB range for adjacent and next-adjacent channels [1]. Many of the previous research works are focused on developing models at the device level for the worst-case and average crosstalk noise and SNR in different ONoCs [11] [3] [16] [2]. They demonstrates that the crosstalk noise is a critical concern in large-scale WDM 3D ONoC. However, we can minimize the worst-case crosstalk noise by spacing out overlapped wavelengths.
Design time and run time approach are employed to allocate wavelengths according to previous work. The wavelength routed based interconnection solutions such as RPNoC [14] and ORNoC [9] employ the design time approach for wavelength allocation. They do not require any arbitration to reserve an optical path before data transmission, since the data payload wavelength is defined between different processors at design time which lead to low scalability. Single-Writer Multiple Readers (SWMR) networks such as Firefly [12] increases bandwidth utilization compared to [14] [9]. The arbitration to avoid conflicting read accesses is done through broadcast of reservation flit on determined channel. Hence, wavelength spacing optimization can not be realised in these architectures.
Multiple-Writers Multi-Reader (MWMR) architecture such as SUOR [15] employ run time wavelength allocation to choose the adapted available bandwidth according to the communication traffic. It makes use of channel grouping method to avoid inter-group contention. In contrast, the channels group restrict the wavelength spacing optimization. In [10], a protocol is proposed to allocate, at run time, the optical communication channels for many core architecture. The reservation always starts by the first free wavelength, and if the first one failed, it will try on the next one, and so on. Thus the overlapped communications have a great chance of using adjacent channel to increase crosstalk. Therefore, run time wavelength allocation is likely to lead a huge crosstalk noise on optical signals.
To the best of our knowledge, none of previous works have explored wavelength spacing for overlapped communication in 3D ONoC. In this paper, we propose to allocate wavelengths at design time on the basis of communication traffic and to optimize wavelength spacing for purpose of reducing crosstalk noise on optical signals.

3. Mathematical formalization of wavelengths spacing optimization

MR is the main optical switching element in 3D WDM ONoC. MR has a lorentzian power transfer function, which is peaked at the resonant wavelength λ_{MR} [11].The amount of this crosstalk noise is determined by the spacing between λ_n and λ_{MR} and 3-dB bandwidth of the MR. The crosstalk noise becomes higher with the smaller channel spacing between λ_n and λ_{MR} . Hence we can space out the overlapped wavelength λ_n and λ_{MR} through wavelength allocation at design time to reduce the crosstalk noise added to the considered wavelength λ_{MR}.

In this section, we describe the architecture of 3D optical many core, the model parameters and especially the proposed heuristic algorithm allows to optimize wavelengths spacing.

3.1. Architecture overview

The formalization of WSO described in next sections can be applied on multiple 3D optical many core. Figure 1 illustrates an example of the considered 3D optical many core. It is composed of an electrical layer implementing $n \times n$ (4×4 in this illustration) IP cores and an optical layer implementing CHAMELEON [8] which are showed in figure 1(a). It is composed of ONIs (Optical Network Interface) (figure 1(b)) crossed by waveguide propagating optical signals. The ONIs facilitate the communication between IP cores through the optical interconnect. Each ONI consists of a receiver part and a transmitter part crossed by a waveguide. The receiver part is composed of wavelength-specific MR that can be turned ON or OFF, in order to respectively configure drop (receive) and pass through operations on the signals at the corresponding wavelength. The transmitter is composed of on-chip laser sources that can emit and inject optical signals at a specific wavelength into the waveguide.
Figure 1(b) illustrates an ONI configuration. The IP_3 is receiving data from IP_1 on wavelength λ_1 (shown in red) which is dropped from the waveguide because of the ON state of MR and photodetector specific to λ_1. The signal at λ_2 (violet color) pass through this ONI, meaning that the receiver for the signal is further along the waveguide (IP_4 in this example). Thus the crosstalk noise appears due to the low channel spacing between λ_1 and λ_2, a part of light from λ_2 will also be filtered by the ON state of MR specific to λ_1 on ONI_3, introducing a non-negligible crosstalk as illustrated in figure 1(b) and figure 1(c). In data transmission, the crosstalk increases the bit error rate of the optical signal. To limit this problem, the choice of wavelength for the communication is important. Indeed, the crosstalk depends on the wavelength frequencies, and more the distance between the frequencies is high, the less the crosstalk will be important.

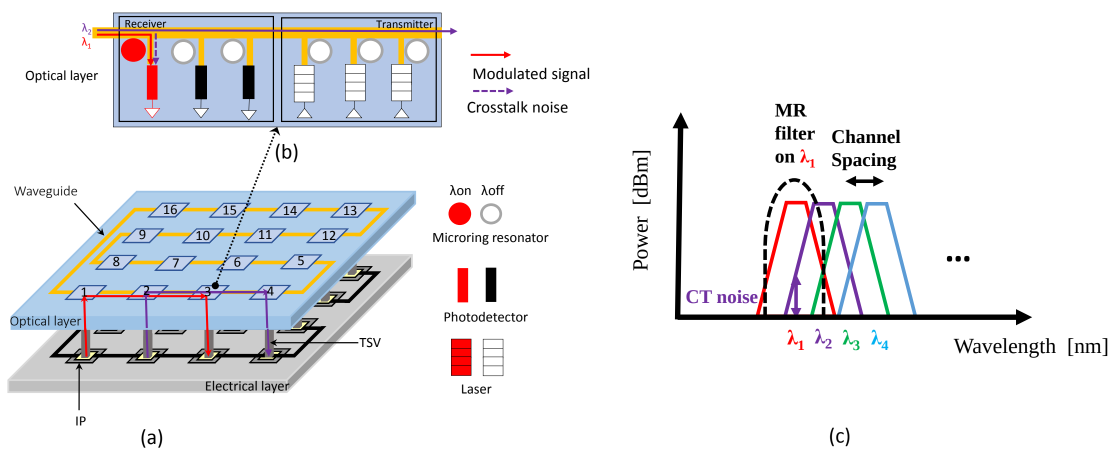

FIGURE 1 – Architecture Overview: (a) 3D optical many core (b) Optical Network Interface (c) Representation of crosstalk in a 4-channel WDM MR

3.2. Model parameters for wavelengths spacing optimization

Firstly some model parameters are defined for expressing the objective function as given below:

- The graph of processors for an application is a directed graph. $\mathcal{G}(\mathcal{P}, \mathcal{C})$ with each vertex $P_i \in \mathcal{P}$ represents the processors connected to the ONoC and the edge $C_{i,j} \in \mathcal{C}$ represents the communication between processor P_i and P_j. The weight of edge $C_{i,j}$ represents the data (Gb) to be transferred from P_i to P_j.

- $CT_{i,j}$ represents the loss (dB/hop), generated by the crosstalk between two wavelengths w_i and w_j sharing same hops in the waveguide. We note that $CT_{i,j}$ is inversely proportional to the distance between frequencies w_i and w_j.
- $W_{i,j}$ is the reserved wavelength (w_m) for the communication between P_i and P_j.
- N_w is the total number of wavelengths in the waveguide which is defined at design time.

3.3. Wavelength allocation for wavelengths spacing optimization

The objective is to space out the wavelengths for overlapped communications at design time in WDM 3D ONoC. The formalization problem can be expressed by an overlapped communications graph defined below.

Definition 1: The overlapped communications graph for an application is an undirected graph, $\mathcal{GC} = \{\mathcal{C}, \mathcal{T}\}$ with each vertex $C_{i,j} \in \mathcal{C}$ represents the communication between P_i and P_j and the edge $T_{C_{i,j},C_{k,l}} \in \mathcal{T}$ represents the overlapped degree between $C_{i,j}$ and $C_{k,l}$. The weight of edge $T_{C_{i,j},C_{k,l}}$ between 2 nodes can be expressed as:

$$T_{C_{i,j},C_{k,l}} = \tau_{C_{i,j},C_{k,l}} \times h_{C_{i,j},C_{k,l}} \tag{1}$$

Where $\tau_{C_{i,j},C_{k,l}}$ is the shared time between overlapped communications $C_{i,j}$ and $C_{k,l}$; $h_{C_{i,j},C_{k,l}}$ is the shared hops between overlapped communications $C_{i,j}$ and $C_{k,l}$. The worst-case crosstalk noise for an application appears where the largest $T_{C_{i,j},C_{k,l}}$ is reached.
The total crosstalk noise (Objective function) can be expressed as (2):

$$\mathrm{Min}\left(\mathrm{Sum}(CT)\right) = \mathrm{Min}\left(\sum_{C_{i,j},C_{k,l} \in \mathcal{GC}} CT_{w_{i,j},w_{k,l}} \times T_{C_{i,j},C_{k,l}}\right) \tag{2}$$

Because the crosstalk is supposed inversely proportional to the distance between w_i and w_j. We would use the index of wavelength instead of wavelength to simplify (2) that gets (3) the Normalized Wavelengths Spacing Optimization (NWSO):

$$NWSO = \mathrm{Min}\left(\sum_{C_{i,j},C_{k,l} \in \mathcal{GC}} \frac{1}{|m-n|} \times T_{C_{i,j},C_{k,l}}\right) \tag{3}$$

Where m and n refer respectively to λ_m and λ_n, i.e. communication $C_{i,j}$ is realised on λ_m and $C_{k,l}$ on λ_n. The smaller NWSO thus represents the less crosstalk noise on optical signals.
We consider that, in our study, all the communications are known (source, destination, exchange volume for each communication) for the application, then $T_{C_{i,j},C_{k,l}}$ can be learned. We can minimize total crosstalk by allocating wavelengths at design time for each communication. Thus, the Branch and Bound algorithm for wavelength exploration is done by minimizing the sum of the inverse of normalized distance between all overlapped wavelengths. The complexity of this method is $O\left({N_w}^{N_n}\right)$, where N_n is the number of nodes in $\mathcal{GC}$.
In this paper we propose a heuristic method that allows to get result faster than Branch and Bound algorithm. The set of edges of $\mathcal{GC}$ is sorted by descending order according to edge value: $T_{sort} = SortUpDown_{by\ edges\ values}(T)$. Our idea is, like greedy algorithm, to follow the priority of weights of edges and make the locally optimal choice at each step, then find a global suboptimal solution. The pseudocode is showed in the algorithm 1. The complexity of sort is $O\left(N_T \ln(N_T)\right)$, where N_T is the number of edges in $\mathcal{GC}$. The complexity of algorithm is $O\left(N_T \times N_w^2\right)$. Therefore the total complexity of our proposed method is $O(N_T \ln(N_T) + N_T \times N_w^2)$ which can be simplified as $O\left(N_T \times N_w^2\right)$.

Algorithm 1 Proposed heuristic algorithm

```
// CalculateCost() is the objective function which calculates NWSO
CurrentSolution = {}
FindSuboptimalSolution(T_sort)
while T_sort != Empty do
  T = ExtractFirstEdge(T_sort)
  T.Communication1.WlAvailable = AllWavelengthsCompatible(T.Communication1)
  T.Communication2.WlAvailable = AllWavelengthsCompatible(T.Communication2)
  CostBestLocalSolution = infinity; BestLocalSolution = {}
  for all λ_i in T.Communication1.WlAvailable and λ_j in T.Communication2.WlAvailable do
    CurrentSolution[T.Communication1] = λ_i
    CurrentSolution[T.Communication2] = λ_j
    CostCurrentSolution = CalculateCost(CurrentSolution)
    if CostCurrentSolution < CostBestLocalSolution then
      BestLocalSolution = CurrentSolution ; CostBestLocalSolution = CostCurrentSolution
    end if
  end for
  CurrentSolution = BestLocalSolution
end while
```

4. Simulation Results

In this section we evaluate the performance of our proposed heuristic algorithm compared with Branch and Bound algorithm and naive method [10]. We target a 16-core chameleon architecture with one waveguide as presented in Fig 1, each communication can reserve only one wavelength.

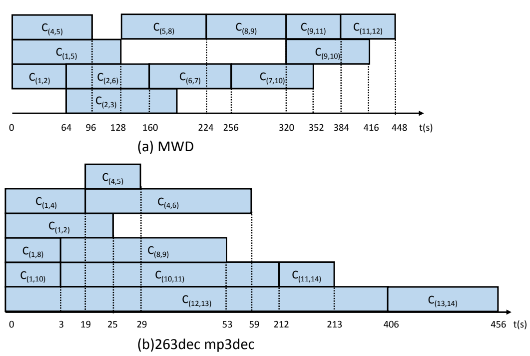

FIGURE 2 – Communication details for MWD and 263dec mp3dec

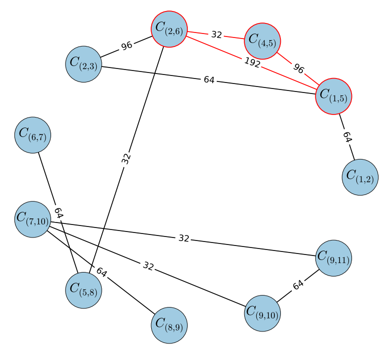

FIGURE 3 – $\mathcal{GC}$ graph for MWD

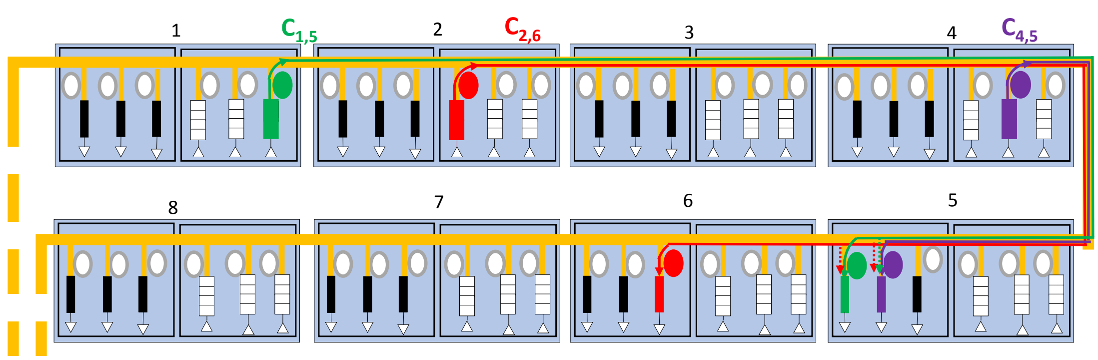

FIGURE 4 – Optical elements state in ONoC for MWD at the 65th second

Fig. 2 notes 2 graphs of communication for MWD and 263dec mp3dec applications [13] where all details (source, destination, start timing, end timing) for each communication are given. For example, P_4 sends data to P_5 during time interval [0, 96] as showed in Fig 2(a). We can illustrate the temporal conflict ($\tau_{C_{i,j},C_{k,l}}$) of different communications in Fig 2 and the spatial one ($h_{C_{i,j},C_{k,l}}$) in Fig 1. The weight of an edge of $\mathcal{GC}$ is not zero if both temporal and spatial conflicts exist. Fig 3 shows the overlapped communication graph of MWD. For example, $C_{1,5}$ and $C_{4,5}$ share one hop ($P_4 \rightarrow P_5$) during time interval [0, 32], thus the weight of edge ($T_{C_{1,5},C_{4,5}}$) between $C_{1,5}$ and $C_{4,5}$ is 1x32 as illustrated in Fig 3. Figure 4 gives state of optical elements due to 3 overlapped communications (3 red vertex illustrated in figure 3) at the 65th seconds for MWD application. 6 MR, 3 photodetectors and 3 on-chip lasers are turned on. Multiple wavelengths sharing a same waveguide for simultaneous communications reaches a MR, leading to inter-channel crosstalk noise due to the imperfection of MR. For example, in the ONI_5, a portion of the signals carried on red and green wavelengths are filtered by the on-state violet MR which introduces crosstalk noise on the violet signal.

We apply our algorithm for wavelength allocation in a 16-core Chameleon ONoC by considering 4 wavelengths in the waveguide. From the table 1, we can see the increase of 14.4% in NWSO of heuristic method 263dec mp3dec and no modification under MWD compared to Branch and Bound algorithm. However, the comparison of optimization time demonstrates that our proposed method is faster (i.e 1.8 ms and 2500 ms for MWD with these two methods respectively). Therefore, the proposed heuristic method is able to achieve an acceptable suboptimal solution with small complexity, even the best solution in some case, to minimize the crosstalk noise. We can see the reduction of 43.75% and 28.9% in NWSO of heuristic method under MWD and 263dec mp3dec respectively in contrast with that of naive method in [10]. The wavelength allocation by proposed heuristic method at design time thus improve the NWSO to reduce the crosstalk.

TABLE 1 – Simulation results: NWSO obtained by the proposed heuristic method and comparison with Branch and Bound method and naive method

Methods / Application	Proposed Heuristic Algorithm		Branch and Bound			Naive Method [10]	
	NWSO	Sim time (ms)	NWSO	Comparison	Sim time (ms)	NWSO	Comparison
MWD	405.33	1.8	405.33	0	2500	720	+43.75%
263dec mp3dec	47.67	0.64	41.67	-14.4%	121	67	+28.9%

Finally, we increase the number of available wavelengths and compare the three methods by varying N_w as presented in Fig. 5 . The NWSO is constant for naive method, because the reservation always starts by the first available wavelength, and if the first one failed, it tries on the next one, and so on. Thus the same solution is obtained by naive method even though more wavelengths are available. However, more N_w gives us more choices and makes the maximal normalized distance of wavelengths greater, thus the reached NWSO refers to the descending curve for another two methods as showed in Fig. 5. As a result we show that our proposed method has a larger improvement in NWSO with more N_w in contrast to naive method [10]. Moreover, the NWSO of proposed heuristic method is more closely to that of Branch and Bound algorithm with the increase of N_w. Therefore, our proposed method performs better with more available wavelengths.

5. Conclusion

In this paper, we have presented a proposed heuristic algorithm for wavelength allocation to minimize the crosstalk noise. The simulation results demonstrate that we can get a suboptimal solution with less complexity, even best solution in some cases, compared to that of Branch and Bound algorithm. Moreover, our method has greatly improved the performance of system compared to naive method [10]. In future work, several wavelengths and several waveguides will be considered for each communication.

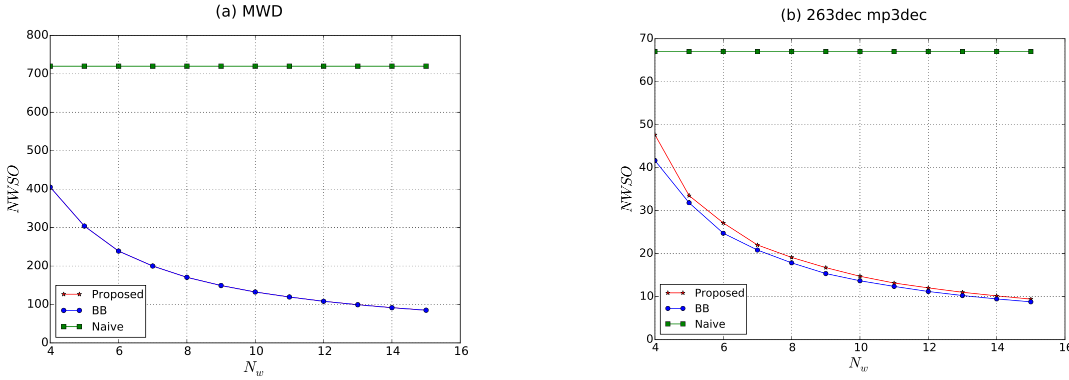

FIGURE 5 – NWSO by varing the number of wavelengths under (a) MWD and (b) 263dec mp3dec

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